ON THE HIGH-FREQUENCY CONDUCTIVITY AND EFFECTIVE DIELECTRIC CONSTANT OF ELECTRONIC MEDIUM IN A (HIGH-VACUUM) THERMIONIC VALVE

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ABSTRACT. In this investigation, the H. F. conductivity of the anode = screen-grid space in a thermionic valve (Philips B 442) was measured under various conditions. Willans' method of measuring H. F. resistance was adopted for the purpose and the double-heterodyne technique was followed in carrying out these measurements. The theory of the method and the experimental procedure are fully described. The conductivity experiments were made in three sections.

(1) Measurements of the conductivity of the inter-electrode space of the thermionic valve for various values of the thermionic current keeping the frequency of the field and time of stay of the electrons constant.

A linear relation was obtained between the conductivity value and the thermionic current.

(2) Measurements of the conductivity of the same electronic medium for different frequencies in the *medium frequency band* for definite values of the electron concentration and time of stay of the electrons.

The conductivity was found to increase with the increase of frequency in this lower range of frequencies.

(3) Measurements of the conductivity of the same electronic medium for different transit-times of the electrons keeping electron concentration and the frequency of the field constant.

The conductivity was found to increase very rapidly with the increase of the time of stay of the electrons.

Measurements were also made of the effective dielectric constant of the inter-electrode space of the same valve to study its variation with the time of stay of the electrons. For a fixed frequency of the field and a definite electron concentration, the effective dielectric constant of the electronic medium was found to decrease very rapidly with the increase in the value of the transit-time of the electrons. Accepting Lorentz's expression for the dielectric constant of a frictionless electronic medium and introducing a multiplying factor it is concluded that this multiplying factor increases with the increase in the time of stay of the electrons in the inter-electrode space of the valve.

INTRODUCTION

The expressions for the dielectric constant and the conductivity of an atmosphere of ions and electrons are now well-known. The corresponding expressions in the case of an electronic medium inside a high-vacuum thermionic valve have not, however, been established with any certainty. Since the time of stay of the electrons in the inter-electrode space is only a small fraction of the period corresponding to the radio-frequency of the alternating field, the contribution of electrons towards the reduction of the dielectric constant should, therefore, be correspondingly small. Benner[1] had considered this effect of the finite time of transit of the electrons on the value of the dielectric constant and also on that of the conductivity of the electronic medium inside a thermionic valve. Recently, however, Hollmann and Thoma[2] deduced from their theory of the inversion of electrons substantially different formulae for the dielectric constant and conductivity of such a medium. Mitra and Sil[3] had also proposed a theory of the conductivity (or resistance) of a thermionic valve. Assuming a Maxwellian distribution of velocity of the electrons inside the valve they calculated the time of flight of the electrons making certain simplifying assumptions and approximately obtained the values of the conductivity of the valve for different frequencies. These values calculated on their hypothesis agreed well with the values found experimentally in the high frequency range. In view of these different theories, it was considered desirable to undertake accurate measurements of the dielectric constant and conductivity of the electronic medium inside a screen-grid valve under different controlled conditions. Some work[4] performed in this laboratory on the effective dielectric constant of such a medium both for medium and ultra-high frequency alternating fields had, however, been previously reported. The present investigation is *primarily* concerned with the experimental determinations of the H. F. conductivity of the anode=screen-grid space of a thermionic valve on *medium* radio-frequencies. The conductivity experiments were made in three sections:

(1) Variation of the H. F. conductivity of the anode=screen-grid space of a screen-grid valve with the thermionic current through the valve, keeping the frequency of the alternating field and the time of stay of the electrons constant.

(2) Variation of the H. F. conductivity of the similar electronic medium with the frequency of the alternating field for definite values of the electron concentration and the time of stay.

(3) Variation of the H. F. conductivity of the similar medium with the time of stay of the electrons keeping the electron concentration and the frequency of the field constant.

The variation of the effective dielectric constant of the electronic medium inside the screen-grid valve with the time of stay of the electrons in the inter-electrode space has also formed a part of this investigation. The experimental results on the H. F. conductivity and the effective dielectric constant of the electronic medium inside the screen-grid valve have been examined and theoretical interpretations given.

METHOD OF CONDUCTIVITY MEASUREMENTS

(a) *Theory of Willans' method of H. F. resistance measurement*

Willans'[5] method of H. F. measurement of resistance was employed in this investigation. The principle involved in the method is the well-known principle of transformer action.

Let us take a secondary circuit containing inductance L_1, resistance R_1 and capacity C_1 in the neighbourhood of an *oscillating* primary circuit containing inductance L, resistance R and capacity C. When a current flows in the secondary circuit, the resistance and reactance of the primary circuit would change (and *vice versa*). The change in the reactance of the oscillator (primary) coil would mean a change of the effective inductance of the same coil, which in turn would cause a change in the emitted frequency of the oscillator. This change in the frequency of the oscillator would be directly proportional to the change of reactance. The frequency-change would be :

$$\Delta f \propto \frac{\omega^2 M^2}{R_1^2 + X_1^2} . X \qquad \dots \quad (1)$$

where X is the reactance of the primary (oscillatory) circuit,
X_1 and R_1 the reactance and resistance of the secondary,
M the mutual conductance between primary and secondary coils,
and ω the angular frequency of the current.

Now it can be easily proved that for ωM=constant, the change of frequency would be maximum, when

$$R_1^2 = X_1^2$$

or

$$R_1 = \pm X_1$$

i.e.

$$\left.\begin{aligned} R_1 &= \left(\omega L_1 - \frac{1}{\omega C_1'}\right) \\ \text{and} \quad R_1 &= \left(\frac{1}{\omega C_1''} - \omega L_1\right) \end{aligned}\right\} \qquad \dots \quad (2)$$

Hence C_1' and C_1'' are the values of the secondary capacity for the two conditions for maximum change of frequency as given in (2). Combining the two conditions, we get

$$R_1 = \frac{1}{2\omega}\left(\frac{1}{C_1''} - \frac{1}{C_1'}\right). \qquad \dots \quad (3)$$

The change in the emitted frequency due to the change in the effective reactance of the oscillatory circuit can be discerned as an alteration of the beat-note in the telephones connected to an oscillating receiver.

(b) Experimental procedure

The experimental procedure is briefly stated here. With the switch of the measurement circuit (L_1 C_1 R_1) open, the frequency of the oscillating receiver is adjusted to the desired value and the frequency of the oscillator is then adjusted by varying its tuning condenser C till no-beat is heard. When the measurement circuit is closed, its condenser C_1 is varied till the beat-note again disappears. This gives the resonance value of C_1. Next displacing C_1 by a small amount, the beat-note is again heard due to the change in the frequency of the oscillator. The tuning condenser C of the latter is now changed till the beat-note again disappears. If the process is repeated for other positions of the condenser C_1 of the measurement circuit, it will be found that the variation of C required to balance the effect of variation of C_1 is of a form with two peaks on both sides of the C_1-value which corresponds to the original frequency. These peaks appear for two different values of C_1, *viz.* C_1' and C_1''. The H. F. resistance R_1 of the measurement circuit can then be calculated from relation (3).

Experimental arrangements and the working formula for the conductivity measurements

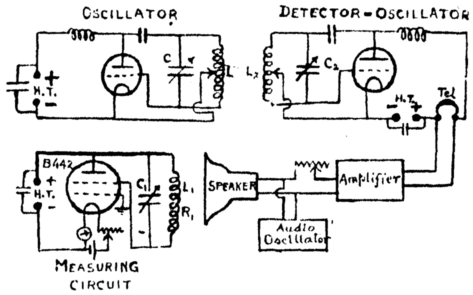

FIG. 1

The complete arrangement of the apparatus is shown in fig. 1. The oscillators were of the Hartley type. A pair of telephones was inserted in the anode circuit of the detector-oscillating valve. When the frequency of each was adjusted, it was possible to hear the heterodyne whistle. The L. F. e. m. f. developed across the telephone was then fed into amplifier of the conventional type. A loudspeaker was connected to the output of the amplifier. Through this loudspeaker was passed an audio-frequency current from the secondary circuit of an audio-oscillator of a suitable constant frequency. A variable resistance was inserted to adjust the amplitude of this audio-frequency current so that the heterodyne whistle and the sound due to the audio-frequency current from the audio-oscillator could be made of the same order of intensity. As a result of the superposition of these two audio-frequency currents through the loud-speaker, beats could be heard. The tuning condenser (C or C_2) of either oscillator could be adjusted till no beats were heard. All the condensers were properly shielded and carefully calibrated. Usually more than one condenser fitted with slow-motion dials were used in parallel with C & C_1.

To determine the H. F. conductivity (or the resistance) of the anode=screen-grid space of the experimental valve, the anode and the screen-grid were then connected to the plates of the condenser C_1 so that C_1 and the inter-electrode capacity C_1 were placed in parallel. A suitable high voltage was applied across the anode and the filament of the valve. Measurements of the H. F. resistance of the measurement circuit with the filament current on and off were then made successively by following the double-beat procedure of Willans' method as previously described. The H. F. resistance R_1' of the circuit when the filament current was switched on was found greater than the corresponding resistance R_1 when the filament current was off. The increase in the resistance $(R_1'-R_1)$ or r was the effect of a leakage across the inter-electrode space due to the conductivity of the electrons in that space. From the value of r obtained experimentally, the corresponding shunt resistance ρ was then calculated from the relation

$$\rho=\frac{1}{\omega^2 r[(C_1)_r+C_r]^2}\approx\frac{1}{\omega^2 r(C_1)_r^2}. \qquad \dots (4)$$

Here $(C_1)_r$ is the resonance value of the condenser C_1 when the inter-electrode capacity C_v was put in parallel with C_1. C_v was very much smaller than $(C_1)_r$.

The H. F. conductivity of the electronic medium in the inter-electrode space as expressed in terms of the leakage shunt-resistance ρ across it was given by

$$\sigma=\frac{1}{4\pi(C_1)_r\rho}. \qquad \dots (5)$$

In view of (4), the conductivity of the electronic medium as expressed in terms of the increase in series resistance r would then be given by

$$\sigma=\frac{\pi C^2}{\lambda^2}\cdot(C_1)_r\cdot r$$

$$=\frac{28.27\times10^{20}\times r}{\lambda^2}\cdot(C_1)_r \qquad \dots (6)$$

Calculations of the conductivity of the medium were made from (6)

EXPERIMENTAL RESULTS

Variation of the H.F. conductivity of the inter-electrode space of the thermionic valve with the thermionic current through it, keeping the frequency of the alternating field and the time of stay of the electrons constant

Measurements of the H. F. conductivity of the anode=screen-grid space of a Philips B 442 valve were made for two different frequencies. For each frequency

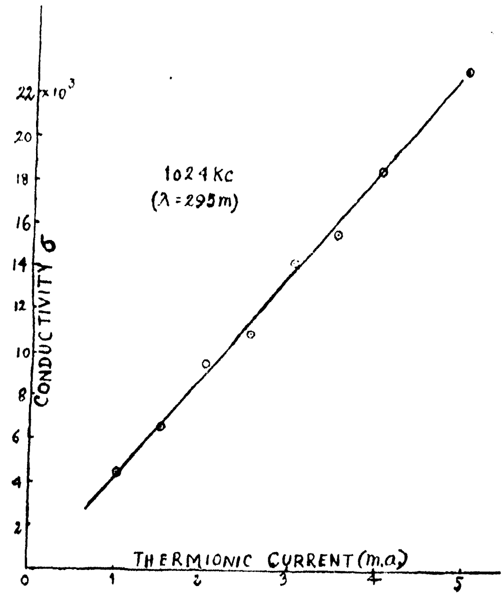

FIG. 2(*a*)

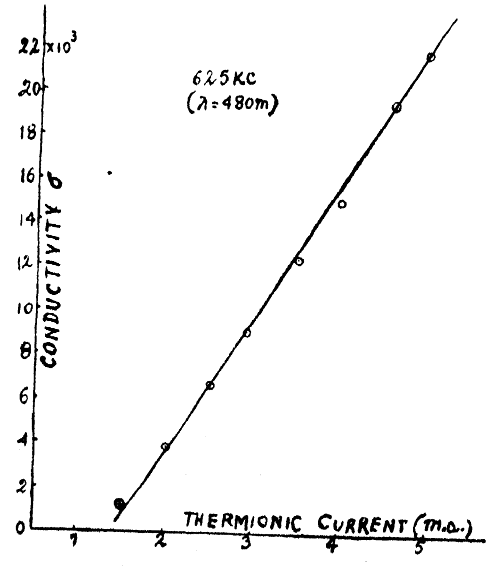

FIG. 2(*b*)

the thermionic current through the valve was varied from 0 to 5 m.a. The results for frequencies : 1024 kc. ($\lambda = 293$ m.) and 625 kc. ($\lambda = 480$ m.) are shown graphically in figs. 2 (a) & 2 (b). A pair of curves drawn from a representative set of observations for the evaluation of the H.F. resistances R_1' & R_1 of the measurement circuit by the method of Willans (when the filament of the experimental valve was switched on and off respectively) are shown in fig. 3.

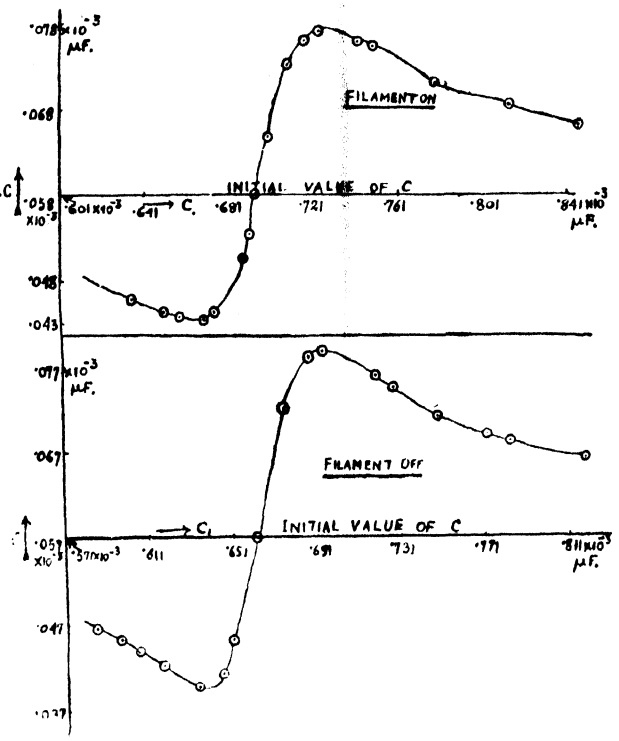

FIG. 3

The curves in fig. 2 show that a linear relation was found in these experiments to hold between the conductivity of the electronic medium and the electron concentration (which could be taken proportionate to the thermionic current since the anode voltage and the filament current were both kept fixed during each set of observations). This linear relationship is expected from any theory of the conductivity of the electronic medium inside a thermionic valve.

Variation of the H.F. conductivity of the inter-electrode space of the thermionic valve with the frequency of the alternating field for definite values of electron-concentration and time of stay of the electrons

In fig. 4 are shown the results of a typical set of experimental results showing the variation of the H.F. conductivity of the anode=screen-grid space of the same thermionic value with the frequency of the alternating field. The thermionic current was fixed at 3.5 m. a. and the frequency was varied from

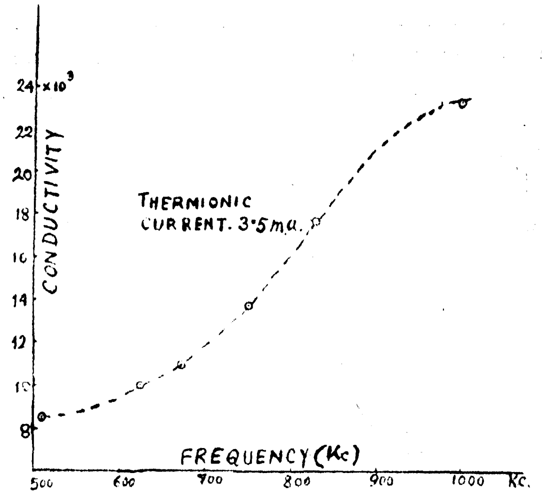

FIG. 4

512 kc. to 1000 kc. ($\lambda = 585$ m. to 300 m.). The conductivity values were calculated with the help of equation (6). It can be seen from fig. 4 that the conductivity *increased as the frequency was increased* within the experimental range, *viz.*, 512 kc. to 1000 kc. It should be mentioned here that the experiments of M. Kameswar Rao[6] performed in this laboratory on the internal resistance of a thermionic valve over a wide range of radio-frequencies revealed the same feature in the lower range of frequencies. He found that the internal resistance of the experimental valve at first decreased with the increase of frequency (till about 1600 kc. in the case of Telefunken RE134 valve and till about 2000 kc. in the case of Philips B406 valve) and that it increased again steadily with the increase of frequency.

Variation of the conductivity of electronic medium inside the valve with the time of flight of the electrons for a definite electron concentration and frequency of the field

In these sets of experiments the anode voltage was varied and *the thermionic current was maintained at a definite value by adjusting the filament current.* Measurements of the H.F. conductivity of the anode = screen-grid space for a definite frequency were then made for different anode voltages. The time of flight of the electrons could be taken as proportional to $\frac{1}{\sqrt{V}}$, where V = anode voltage. In fig. 5 are shown the results of a typical set of experiments for a definite frequency of the field. It is significant that the value of the conductivity

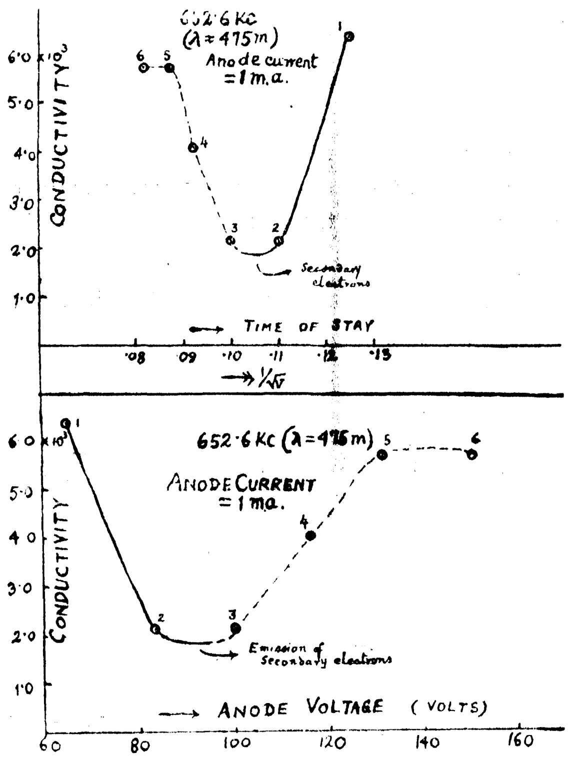

FIG. 5

decreased very rapidly with the increase of the anode voltage up to about 90 volts and then increased steadily tending to approach a limiting value. The increase of conductivity at about 90 volts must be due to the secondary electrons emitted at the anode and screen-grid surfaces. Before the emission of the secondary electrons, the experiments indicated a very rapid increase of the conductivity with the time of stay of the electrons.

DISCUSSION OF THE EXPERIMENTAL RESULTS ON THE CONDUCTIVITY OF THE ANODE-SCREEN-GRID SPACE OF THE THERMIONIC VALVE

We shall write below the expressions for the conductivity term as given by Benner and Hollmann & Thoma :

$$\text{Benner :} \quad \sigma = \frac{Ne^2}{m\omega^2 T}(1 - \cos \omega T) \qquad \ldots (7)$$

$$\text{Hollmann \& Thoma}: \quad \sigma = \frac{Ne^2T}{m}\left[\frac{\sin\frac{\omega T}{2} - \frac{\omega T}{2}\cdot\cos\frac{\omega T}{2}}{\left(\frac{\omega T}{2}\right)^2}\cdot\sin\frac{\omega T}{2}\right] \quad \ldots \quad (8)$$

where N = electron concentration,
T = time of stay of the electrons in the inter-electrode space,
ω = angular frequency of the field,
and e, m are charge and mass of an electron.

When ωT is sufficiently small, these equations will reduce to :—

$$\text{Benner}: \quad \sigma = \frac{Ne^2T}{m} \quad \ldots \quad (9)$$

$$\left.\begin{array}{r}\text{Hollmann \&}\\ \text{Thoma}:\end{array}\right\} \sigma = \frac{Ne^2T}{m}\left(\frac{\omega T}{6}\right).\sin\left(\frac{\omega T}{2}\right)$$

$$= \frac{Ne^2\omega T^2}{6m}\left[\frac{\omega T}{2} - \frac{\omega^2T^3}{48}\right]$$

$$\simeq \frac{Ne^2\omega^2T^3}{12m}. \quad \ldots \quad (10)$$

Let us now consider our experimental results on the conductivity of the electronic medium inside the valve.

(a) Relation between the conductivity σ and the electron concentration N for fixed values of frequency and time of stay of the electrons

The observed linear relation between the conductivity of the anode = screen-grid space and the thermionic current (which could be taken as proportional to the electron concentration since the anode voltage and filament current were kept fixed) can be explained on either formula. Exact quantitative comparison between the experimental values and the values expected from either formula is not, however, possible since the time of stay of the electrons from the filament in the inter-electrode space is not accurately known. Accepting, however, an approximate estimate of T equal to 10^{-9} sec., we can find out the order of magnitude of the electron concentration N in the inter-electrode space. Taking the experimental value of the conductivity σ to be 10^4, N comes out to be 4×10^3 according to Benner's formula, whereas according to Hollmann & Thoma, N is of the order of 10^{10}. The former value is incredibly small and the latter is again too large under the conditions of our experiments.

(b) Relation between the conductivity and the frequency of the field for fixed values of electron concentration and time of stay of the electrons

According to Benner σ is independent of the frequency of the field. Benner's formula, therefore, cannot explain the observed variation of conductivity of the electronic medium inside the valve with the frequency of the field. A little inspection of Hollmann & Thoma's formula will show that the conductivity should increase with the increase of frequency for values of ωT from 0 to $\frac{\pi}{2}$. For very small values of ωT, however, σ should vary as the square of the frequency as is evident from (10). It should be noted that for 100 megacycles frequency ($\lambda = 3$ metres), $\omega T = .4 \times \frac{\pi}{2}$, assuming $T = 10^{-9}$ sec. For lower frequencies, ωT is still less. In the medium frequency range, ωT is only a very minute fraction of $\pi/2$. Thus, according to Hollmann & Thoma, the conductivity term should increase with frequency from very low to very high frequencies. Our experiments *on the medium frequency band* showed this increase of conductivity with frequency but experiments with higher frequencies performed in this laboratory and elsewhere had definitely shown a steady diminution of conductivity of the inter-electrode space of a thermionic valve with frequency. We have already referred to Rao's work in this laboratory showing a gradual decrease and then a steady increase of the internal resistance of a thermionic valve with the increase of frequency of the measuring field. Hollmann & Thoma's formula can, therefore, be regarded as untenable. Khastgir [7] has recently explained the observed variation of the resistance of a thermionic valve over a wide range of frequencies. Accepting the fundamental ideas of Mitra & Sil about the conductivity of a valve arising from the convection current and considering also the conductivity due to the displacement currents, it has been shown that the experimental results on the variation of the conductivity of the valve with frequency can be interpreted.

(c) Effect of the time of stay of the electrons on the value of the conductivity

Our experiments showed that for the larger values of the time of stay of the electrons, the conductivity increased very rapidly with the time of stay. Both Benner's and Hollmann & Thoma's formulae, however, demand that the conductivity of the valve should increase with the time of stay of the electrons. The observed increase was rather much too rapid.

Measurements of effective dielectric constant of the inter-electrode space in the valve and its variation with the time of stay of the electron

(*a*) *Theoretical considerations*

We shall write below the expressions for the change in the dielectric constant of the electronic medium inside a valve as given by Benner and Hollmann & Thoma.

Benner :
$$\Delta\epsilon = -\frac{4\pi Ne^2}{m\omega^2}\left(1-\frac{\sin\omega T}{\omega T}\right) \qquad \ldots \quad (11)$$

Hollmann & Thoma :
$$\Delta\epsilon = \frac{2\pi Ne^2T^2}{m} \cdot \frac{\sin\frac{\omega T}{2} - \frac{\omega T}{2} \cdot \cos\frac{\omega T}{2}}{\left(\frac{\omega T}{2}\right)^3} \cos\frac{\omega T}{2} \, . \qquad \ldots \quad (12)$$

When $\omega . T$ is sufficiently small, both these expressions are reduced to

Benner :
$$\Delta\epsilon = -\left(\frac{2\pi N}{3m}\right)T^2 \qquad \ldots \quad (13)$$

Hollmann & Thoma :
$$\Delta\epsilon = \frac{2\pi Ne^2T^2}{m} \cdot \frac{\omega T}{6} = (\tfrac{1}{3}\,\pi Ne^2\omega).T^2. \qquad \ldots \quad (14)$$

The experiments[8] performed in this laboratory had previously shown that both the above expressions for the dielectric constant of electronic medium were untenable. A multiplying factor was introduced in the Lorentz formula for the dielectric constant of a frictionless electronic medium to obtain the effect of the time of stay of the electrons in the inter-electrode space. Expressing this multiplying factor in the form

$$\mu = \frac{A}{\lambda} \cdot f(T),$$

where A is a constant, T the transit-time, and λ the wavelength of the field, it was shown that μ was independent of $\left(\frac{A}{\lambda}\right)$ and depended *only* on the time of transit of the electrons. The experiments described in this section were undertaken to find the nature of this dependence.

(*b*) *Experimental arrangement and procedure*

The experimental technique was essentially that of the double-beat method adopted in the previous work on the subject (*vide* fig. 6.)

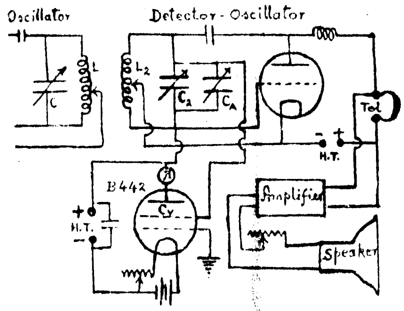

FIG. 6.

The anode = screen-grid capacity C_r of the same valve (Philips B442) was placed in parallel with the tuning condenser C_2 of a detector-oscillator circuit. The change in the capacity of C_r when the inter-electrode space was filled with electrons was balanced by changing the capacity of an accurately calibrated small variable vernier air condenser C_A in parallel with C_r and C_2, so that the total capacity $(C_r + C_2 + C_A)$ remained constant. The high frequency signal from an oscillator was received by the oscillator-detector valve-circuit which was exactly similar to the oscillator circuit. When the detector circuit was nearly in tune with the oscillator, the familiar heterodyne whistle was heard in the telephone placed in the anode circuit of the receiver. The audio-frequency voltage developed across the telephones was then amplified by a suitable amplifier and fed into a loudspeaker which gave a loud musical note. On introducing into the same loudspeaker an audio-frequency current from a specially constructed audio-oscillator capable of producing an intense note of fixed frequency, beats were heard by suitably adjusting the heterodyne frequency. (A variable resistance was placed in series with the secondary coil of the audio-oscillator to match the intensity of the heterodyne whistle with that of the audio-frequency note). Adjustments of the variable vernier condenser C_A in the oscillator to produce no beats were then made successively *first* when the inter-electrode space was devoid of electrons and *next* when the same space was filled with the electrons. In other words, the change in the capacity of C_A was noted with the filament of the experimental valve off and on after having given suitable high voltages to the anode and the screen grid. In this observed change in capacity ΔC was added a correction $(\Delta C)_\sigma$ to allow for the effect of the conductivity of the medium. The change in the capacity due to the dielectric constant change *alone* would then be given by

$$(\Delta C)_\epsilon = \Delta C + (\Delta C)_\sigma .$$

The dielectric constant was thus calculated from

$$\epsilon = 1 - \frac{(\Delta C)_\epsilon}{C_v} . \qquad \cdots \quad (15)$$

It was, therefore, necessary to determine *first* the observed change in capacity ΔC for different anode and screen-grid voltages (with suitable values of filament current to keep the thermionic current constant) and then to find the correction term $(\Delta C)_\sigma$.

(c) *Correction for the conductivity of the electronic medium*

After determining the observed decrease in the capacity ΔC for each different anode voltage in the way described before, the correction term for the conductivity effect was obtained in the following way :

The H. F. series-resistance of the electronic medium was measured by Willans' method for each different anode voltage, keeping the thermionic current constant. The corresponding shunt resistance ρ was then calculated by the standard formula. A graph was then drawn showing ρ against the anode voltage. Next in a separate experiment the inter-electrode capacity was shunted by different non-inductive metal film high resistances and the corresponding increase in the effective capacity of the oscillating system necessary to restore resonance condition was accurately measured by following the double-beat method already described. Another graph was then constructed from the observed data showing the increase in the capacity against the value of the metallised shunt resistance employed. From these two graphs the correction terms $(\Delta C)_\sigma$ (for the different values of the shunt resistance ρ corresponding to the H. F. series-resistances γ of the electronic medium) were obtained for different anode voltages and a correction graph constructed showing correction $(\Delta C)_\sigma$ for the different anode voltages. To each value of the observed decrease in capacity obtained in the main experiment for each different anode voltage, the requisite value of $(\Delta C)_\sigma$ obtained from the correction graph was then added. This gave the change in the capacity $(\Delta C)_\epsilon$ due to the dielectric constant change alone.

(d) *Experimental results*

The results of a typical set of experiment are shown in fig. 7 and the data are entered in the table below :

Serial No.	V Anode Voltage (volts)	$t \propto \frac{1}{\sqrt{V}}$ $\frac{1}{\sqrt{V}}$	ΔC $(\mu\mu f)$	$(\Delta C)_\sigma$ $(\mu\mu f)$	$(\Delta C)_\epsilon = \Delta C + (\Delta C)_\sigma$ $(\mu\mu f)$	$\epsilon = 1 - \frac{(\Delta C)_\epsilon}{C_\nu}$
1	65	.125	2.8	1.99	4.79	.52
2	83	.110	1.65	1.00	2.65	.735
3	100	.100	1.55	1.00	2.55	.745
4	118	.093	1.9	1.99	2.89	.71
5	135	.087	2.2	2.8	5.0	.50
6	150	.082	2.5	2.9	5.4	.46

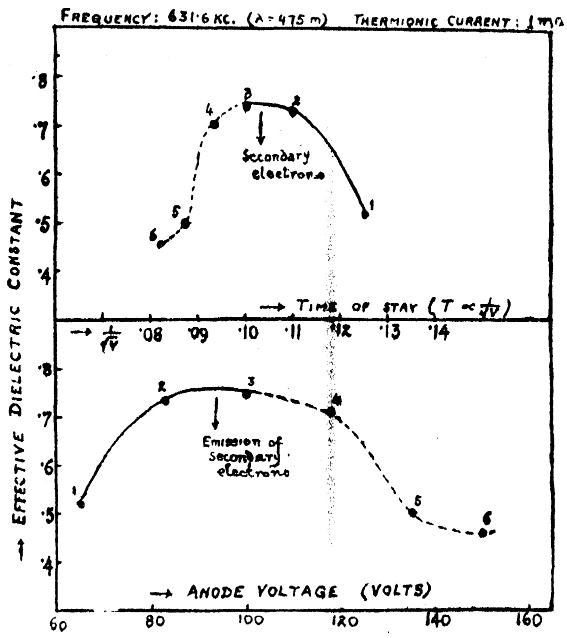

FIG. 7

It can therefore be said that, before the emission of the secondary electrons, the effective dielectric constant of the electronic medium increased with the anode voltage, *i.e.*, it *decreased* with the time of stay of the electrons.

(*e*) *Discussion of the experimental results and conclusion therefrom*

From Benner's and Hollmann and Thoma's expressions for the dielectric constant of electronic medium in a thermionic valve, we find that the dielectric constant in the former case would *decrease* with the increase of the time of stay T and that in the latter case it would *increase* with the transit time of the electrons. According to Hollmann and Thoma, however, the dielectric constant would be greater than unity for the given value of ωT. In view of the results of experiments performed in this laboratory and already referred to, we consider both formulae untenable. Accepting, however, Lorentz's formula for the dielectric constant of a frictionless electronic medium with a multiplying factor μ in it and neglecting the Lorentz term, *viz.*,

$$\epsilon = 1 - \frac{4\pi(N\mu)e^2}{m\omega^2} \qquad \ldots \quad (16)$$

we conclude that as the effective dielectric constant was found to decrease with the increase of the time of stay of the electrons, the factor μ, would *increase* with the increase of the transit-time T.

ACKNOWLEDGMENTS

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